An Interactive Demonstration of Electromagnetic Wave Propagation Using Time-Domain Finite Differences

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***Abstract*—The finite difference time-domain (FDTD) method is one of the most widely used computational methods in electromagnetics. Using FDTD, Maxwell's equations are solved directly in the time domain via finite differences and time stepping. The basic approach is relatively easy to understand and is an alternative to the more usual frequency-domain approaches.**

In order to take advantage of this, an interactive personal computer program based on FDTD has been developed. The program directly solves Maxwell's equations via finite differences. The solution is for one dimension, corresponding to normal incidence propagation through a planar stratified medium. The program displays an electromagnetic pulse as it propagates through the medium. Most textbooks devote very little space to time-domain solutions, but instead emphasize a complex time-harmonic approach. While there are good reasons for this, a time-domain demonstration provides a much more intuitive view of wave propagation.

While the program can be used as a visual "bounce diagram" movie, it is much more versatile. Since Maxwell's equations are solved directly, the reflected and transmitted pulse amplitudes demonstrate how the reflection and transmission coefficients determine reflected and transmitted wave amplitudes. Since lossy material layers can be included, frequency dispersion can be demonstrated.

If the student's background permits, an FFT can be used to transform the time domain results to the frequency domain to obtain, for example, complex reflection and transmission coefficients for a dielectric slab for comparison to results obtained via frequency domain transmission line techniques. At the graduate level, the program can be used to demonstrate the FDTD technique as a powerful tool for solving real-world electromagnetic scattering and coupling problems.

I. Introduction

Classroom demonstrations using personal computers (PC's) are considered to be very useful teaching tools. Even more useful are interactive PC programs which are controlled by the student and which illustrate the phenomena being considered. Programs which illustrate pulses traveling back and forth on a transmission line, "bounce diagram" movies, are easy to develop and readily available. However, this type of demonstration is quite limited. They assume pulses with zero rise time which nevertheless propagate without dispersion, definitely not illustrating actual phenomena.

The approach presented in this paper involves a PC demonstration program which is based on an actual solution of Maxwell's equations. The calculations are performed via the finite difference time-domain (FDTD) technique [1], which actually solves Maxwell's differential equations via finite differences. To simplify the graphical displays, the geometry has been made one dimensional, so that the solution is actually for a plane wave normally propagating through a planar stratified medium. Each layer may have its permittivity, permeability, and conductivity specified, although to provide reasonable menu choices, the geometries which can be specified interactively are limited.

Even at the undergraduate level, the FDTD formulation can be presented, and in fact for most students, it is more readily understood than the usual time-harmonic approach. This lets the students understand the theoretical basis for the graphics displayed and the menu choices available.

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If the student's background permits, an FFT is provided to transform the time-domain results to the frequency domain to obtain, for example, complex reflection and transmission coefficients for a dielectric slab for comparison to results obtained via frequency-domain transmission line techniques. At the graduate level, the program can be used to demonstrate the FDTD techniques as a powerful tool for solving real-world electromagnetic scattering and coupling problems.

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II. One-Dimensional FDTD Formulation

In order to reduce the complexity of programming and displaying FDTD computations, we formulate the difference equations in one dimension. If we arbitrarily choose to retain E_y and H_z with propagation in the x direction, then Maxwell's equations become

$$\frac{\partial E_y}{\partial t} = -\frac{1}{\epsilon}\left(\frac{\partial H_z}{\partial x} - \sigma E_y\right) \tag{1}$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu}\frac{\partial E_y}{\partial x}. \tag{2}$$

Following Yee's [1] notation, we let $x = i \cdot \Delta x$, $t = n \cdot \Delta t$, and $F^n(i) = F(i \cdot \Delta x, n \cdot \Delta t)$ where F is any field component. Still following Yee's approach, we interleave E_y and H_z in space and time, and specify ϵ, μ, and σ at discrete points (actually, layers for our 1-D formulation). After approximating the differential equations as difference equations and simplifying, we easily obtain

$$E_y^{n+1}(i) = \left(\frac{\epsilon(i)}{\epsilon(i) + \Delta t \sigma(i)}\right) E_y^n(i) - \frac{\Delta t}{\Delta x(\epsilon(i) + \Delta t \sigma(i))} \cdot \left[H_Z^{n+1/2}(i + 1/2) - H_Z^{n+1/2}(i - 1/2)\right] \tag{3}$$

$$H_Z^{n+1/2}(i + 1/2) = H_Z^{n-1/2}(i + 1/2) - \frac{\Delta t}{\Delta x \mu(i + 1/2)} \cdot \left[E_y^n(i + 1) - E_y^n(i)\right]. \tag{4}$$

Equations (3) and (4) are readily programmed for solution by iteration of each equation alternately.

The next considerations are the stability and accuracy constraints on Δx and Δt. It must be pointed out that Δx must be much less than the minimum wavelength of interest and the minimum scatterer dimension for good accuracy. For stability, time steps must be small enough so that field values can affect only nearest neighbors during one time step internal. For our one-dimensional equations, a necessary stability criterion is

$$c \cdot \Delta t < \Delta x \tag{5}$$

where c is the speed of light. A conservative choice is

$$c \cdot \Delta t = 0.5 \cdot \Delta x \tag{6}$$

and this is used in the demonstration model.

We must also consider excitation of the difference equations. One can discuss different pulse shapes relative to their frequency content. A traditional choice is the Gaussian pulse. If we let E_0 be the peak amplitude, x_p be the original location of the peak, and $2 \cdot w \cdot \Delta x$ be the pulse width to $0.001 \cdot E_0$ amplitude, then the Gaussian pulse electric field is given by

$$E_y = E_0 \exp\left[-\beta(x - x_p - ct)^2\right] \tag{7}$$

with

$$\beta = \frac{\ln(0.001)}{(w \cdot \Delta x)^2} = \frac{\ln(0.001)}{(w \cdot 2 \cdot c \cdot \Delta t)^2}. \tag{8}$$

Writing (7) as a difference equation suitable for exciting a propagating wave, we have, with x_p locating the initial position of the pulse peak,

$$E_y^0(i) = E_0 \exp\left[-\ln(0.001) \cdot \left(\frac{i - x_p/\Delta x}{w}\right)^2\right]. \tag{9}$$

For propagation in the plus-x direction, the corresponding magnetic field is given as

$$H_Z^{1/2}(i + 1/2) = \frac{E_0}{Z_0} \exp\left[-\ln(0.001) \cdot \left(\frac{i - x_p/\Delta x + 1/4}{w}\right)^2\right] \tag{10}$$

where Z_0 is the impedance of free space.

The final consideration before programming the above equations is absorbing pulses as they are incident at the limits of the problem space. Significant literature exists on FDTD absorbing boundary conditions, but as our problem formulation allows only normal incidence, the problem is considerably simplified over 2-D and 3-D formulations. An adequate absorbing boundary condition is given by Mur [2] which can be reduced to one dimension. Some examples of the results which can be obtained using the one-dimensional FDTD formulation are illustrated in Figs. 1–3. The geometry consisted of a one-dimensional stratified medium with 512 layers. The medium is free space except for layers 250–309 which are some type of dielectric. Layer 310 may be specified as a perfect absorber. Each layer (Δx) is 1.5 mm, so the dielectric slab is 9 cm thick.

Fig. 1 shows a sequence of plots of electric field versus position for an incident 400 ps (to 0.001 amplitude) Gaussian pulse at different time steps. The dielectric slab has a relative permittivity of 4. The propagation and reflection of the pulse(s) are clearly visible.

In Fig. 2, the same geometry is considered except that the dielectric slab has relative permittivity 4 and conductivity 1 S/m. In this sequence of plots, the dispersion of both the reflected and transmitted pulse is evident, as is the attenuation of the pulse which travels through the lossy dielectric.

In Fig. 3, the dielectric slab is lossless with relative permittivity of 4, but the incident pulse is shortened to 100 ps. This sequence of plots illustrates what happens if one of the fundamental limitations ($\Delta x << $ minimum wavelength) is violated. The shorter pulse with greater high-frequency energy rapidly breaks up due to numerical instabilities.

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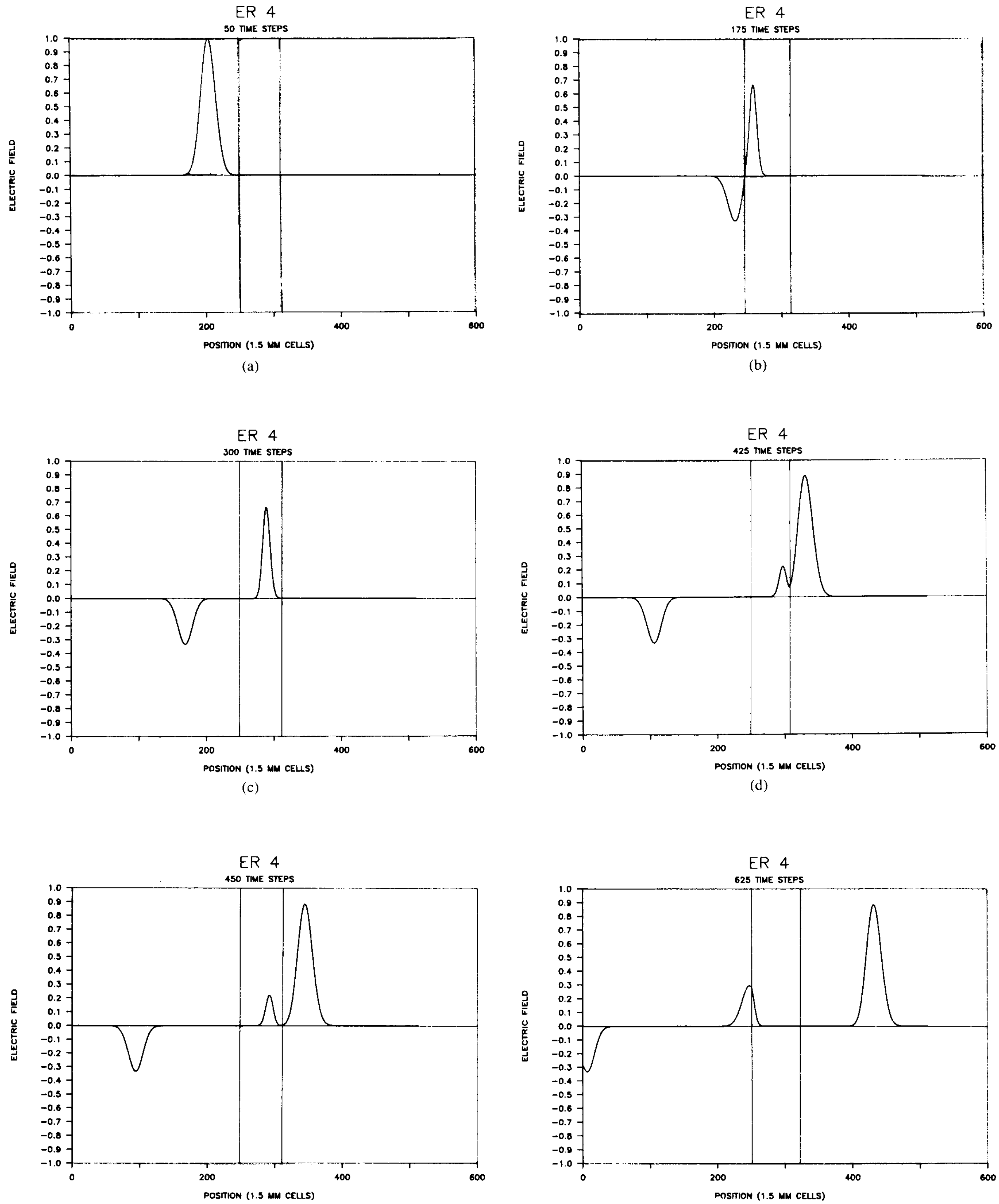

Fig. 1. Interaction of a Gaussian pulse plane wave with a dielectric slab of relative permittivity 4.0, 9 cm thick, located between delta-x positions 250 and 309, calculated using FDTD. Plots are of electric field versus delta-x position after various numbers of time steps: (a) 50 time steps, (b) 175 time steps, (c) 300 time steps, (d) 425 time steps, (e) 450 time steps, (f) 625 time steps. Each time step is 2.5 ps.

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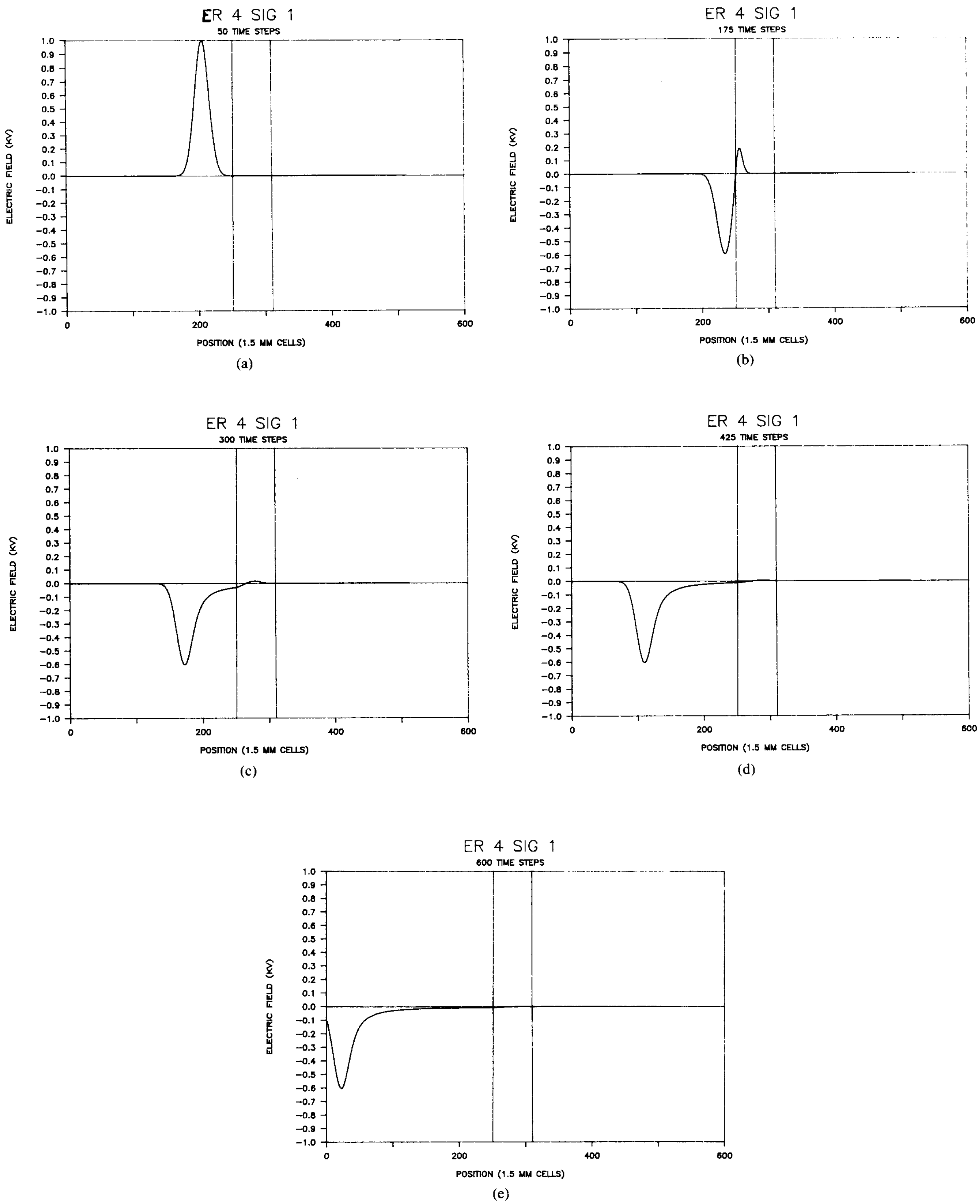

Fig. 2. Interaction of a Gaussian pulse plane wave with a dielectric slab of relative permittivity 4.0, conductivity 1.0 S/m, 9 cm thick, located between delta-x positions 250 and 309, calculated using FDTD. Plots are of electric field versus delta-x position after various numbers of time steps: (a) 50 time steps, (b) 175 time steps, (c) 300 time steps, (d) 425 time steps, (e) 600 time steps. Each time step is 2.5 ps.

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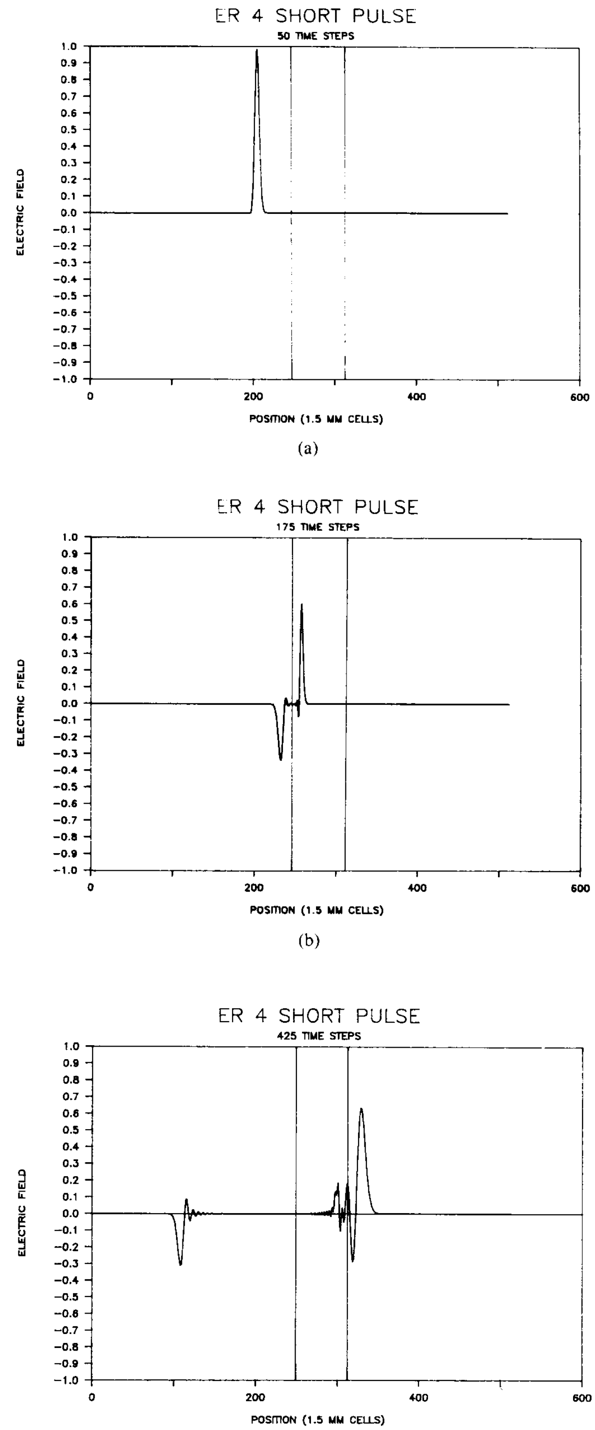

Fig. 3. Interaction of a Gaussian pulse plane wave with a dielectric slab of relative permittivity 4.0, 9 cm thick, located between delta-x positions 250 and 309, calculated using FDTD. The pulse length is 1/4 that of Figs. 1 and 2, and the results illustrate the effect of violating one of the limitations of the FDTD method. Plots are of electric field versus delta-x position after various numbers of time steps: (a) 50 time steps, (b) 175 time steps, (c) 425 time steps. Each time steps is 2.5 ps.

III. Transformation to Frequency Domain

The effect of frequency content of the Gaussian pulse on pulse dispersion leads naturally to consideration of transforming the time domain results to frequency domain. One can begin by calculating the bandwidths of the 400 and 100 ps pulses used previously and showing that the shorter pulse contains significant energy at frequencies such that the constraint of $\Delta x \ll$ minimum wavelength is violated, explaining the dispersion of the pulse.

The next step is to actually transform calculation results to the frequency domain. The example which was chosen to illustrate this was determination of the frequency domain reflection coefficient for a pulse incident on a slab from FDTD time domain computations.

We have already seen samples of time-domain calculations in Figs. 1–3. Similar calculations must progress through enough time steps so that the pulse amplitudes have decreased to very low values. The electric field amplitude at the x coordinate just in front of the dielectric is stored versus time. This results in values of total electric field versus time at the surface of the slab ($E^n_{\text{tot}}(i_f)$). We then remove the slab and excite the problem again with free space everywhere, again saving the electric field versus time at the same location as before. This gives us the incident electric field at the front of the slab ($E^n_{\text{inc}}(i_f)$) versus time. For each time step, the reflected field is given by

$$E^n_{\text{ref}}(i_f) = E^n_{\text{tot}}(i_f) - E^n_{\text{inc}}(i_f). \qquad (11)$$

This is illustrated in Fig. 4 for the 9 cm thick dielectric slab with $\epsilon_r = 4.0$.

For our example problems, it was found that taking 4096 total time steps was sufficient to determine the total field. The incident field could be determined with just enough time steps to allow the incident pulse to pass by the position of the slab interface, with zeros used to pad the incident field to 4096 if necessary. Let us denote T as the number of time steps to determine the total field (4096 for our examples) and I as the number of time steps for the incident field (256 was sufficient for this). For the examples shown, $\Delta x = 0.0015$ m, $\Delta t = 2.5$ ps, the Gaussian pulse width is 400 ps ($w = 40$), and all dielectric slabs are 9 cm ($60 \cdot \Delta x$) thick.

The discrete Fourier transform (DFT) is given by

$$e(k\Delta f) = \Delta t \sum_{n=0}^{N-1} E^n(i_f) \exp\left[-j2\pi nk/N\right]. \qquad (12)$$

After considering the slab thickness relative to the frequency content of the Gaussian pulse, it seemed desirable to have results at frequency intervals of approximately 25 MHz. For a power of 2 transform, we chose N as 16 384, resulting in $\Delta f = 1/(N \cdot \Delta t) = 24.414$ MHz. We further estimated that our maximum frequency of interest would be 5 GHz, so that we were interested in the first 205 frequencies ($k = 1, 205$) of the DFT. Our DFT expressions

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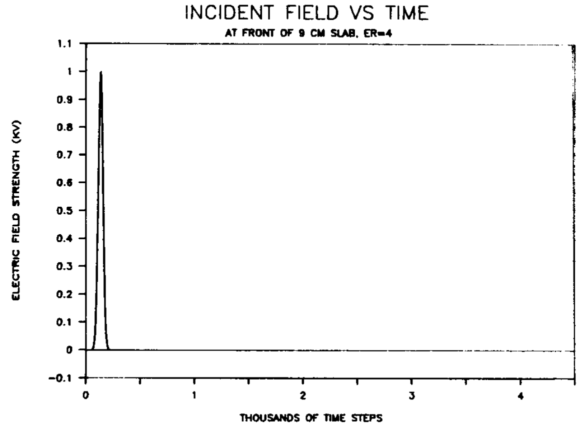
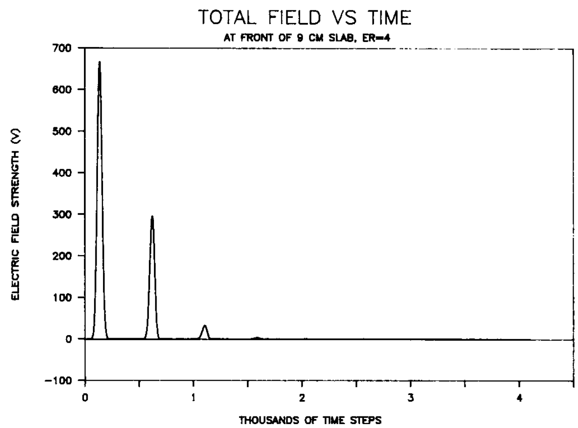
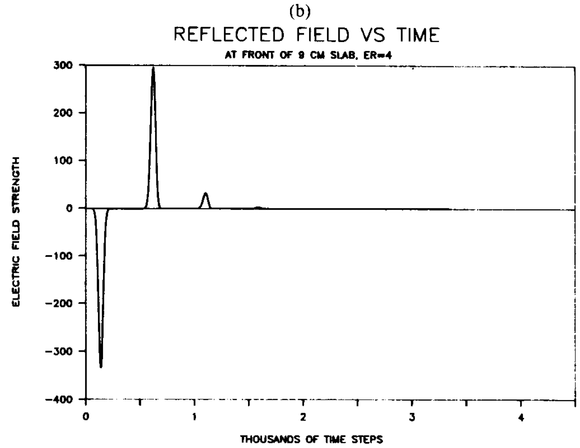


(a)



(b)



(c)

Fig. 4. Electric field strength versus time just in front of a dielectric slab of relative permittivity 4.0, 9 cm thick for Gaussian pulse plane wave incidence calculated using FDTD. (a) Incident field, (b) total field, (c) reflected field.

for the incident and reflected fields became

$$e_{\mathrm{inc}}(k\Delta f) = \Delta t \sum_{n=0}^{I} E^n_{\mathrm{inc}}(i_f) \exp\left[-j2\pi nk/N\right] \quad (13)$$

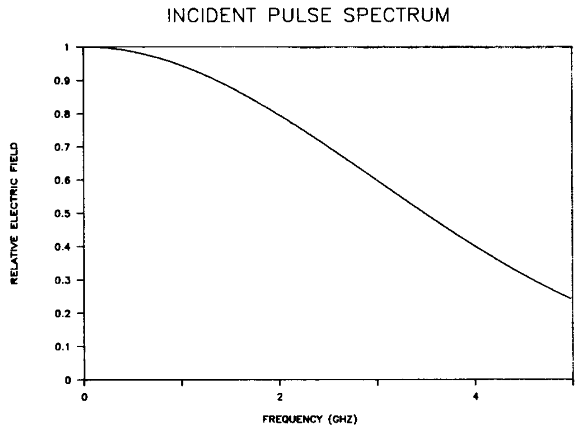


Fig. 5. Fourier transform of the incident Gaussian pulse of Fig. 4(a).

$$e_{\mathrm{ref}}(k\Delta f) = \Delta t \sum_{n=0}^{T} E^n_{\mathrm{ref}}(i_f) \exp\left[-j2\pi nk/N\right] \quad (14)$$

with the frequency-domain complex reflection coefficient $R(f)$ given by

$$R(k\Delta f) = \frac{e_{\mathrm{ref}}(k\Delta f)}{e_{\mathrm{inc}}(k\Delta f)}. \quad (15)$$

The above computations could have been done somewhat faster using an FFT algorithm. But the savings of using the FFT versus the direct computation would be diminished since we are only interested in 205 values out of 16 384 and since we only have 4096 nonzero terms in our direct summation.

Let us consider some examples of applying the above transforms. First, we show in Fig. 5 the frequency spectrum of our incident Gaussian pulse computed from (13). This incident pulse is used for all of the following reflection coefficient computations. Normalizing the reflected to the incident field for computation of the reflection coefficient as indicated in (15) simultaneously corrects for the frequency rolloff of the incident pulse while providing the phase reference for the reflection coefficient.

Reflected pulse spectra and reflection coefficient versus frequency for a slab with $\epsilon_r = 4$, 9 cm thick, is shown in Fig. 6. Note that the slab has a minimum reflection coefficient (it should be exactly zero) when the slab is a multiple of $1/2$ wavelength thick, and a maximum reflection coefficient of 0.6 at odd multiples of $1/4$ wavelength in thickness, as it should. The accuracy decreases at higher frequencies, a characteristic of incident pulse FDTD computations.

Fig. 7 is the reflection coefficient versus frequency for the same 9 cm thick $\epsilon_r = 4$ slab, but backed by a perfect conductor. The reflection coefficient magnitude should be exactly 1 for all frequencies, but a periodic error, greatest when the slab is an odd multiple of $1/4$ wavelength thick, is evident in the results, with the error being greater at high frequencies, as expected.

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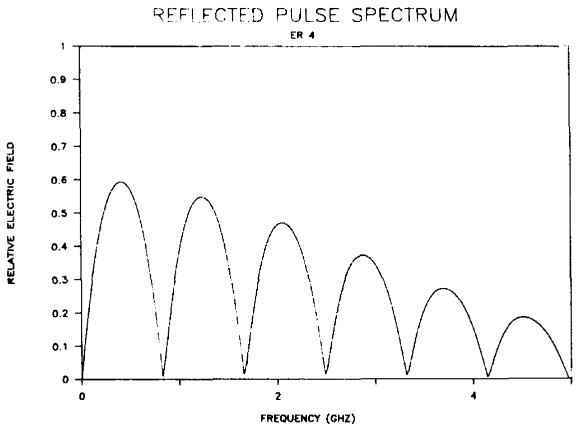
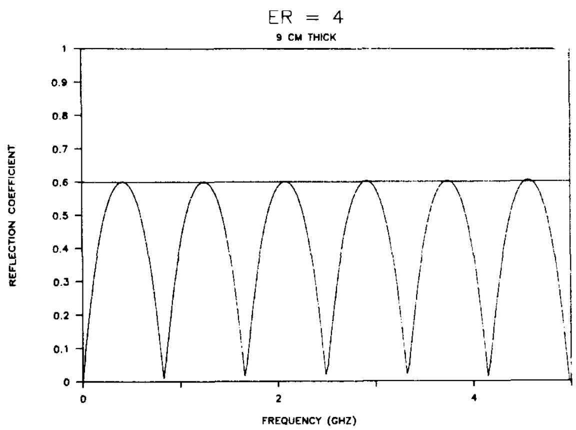


(a)



(b)

Fig. 6. Fourier transform of reflected field of Fig. 4(c) and corresponding reflection coefficient versus frequency (based on FDTD) for a dielectric slab of relative permittivity 4.0, 9 cm thick. The exact result ranges between 0 and 0.6

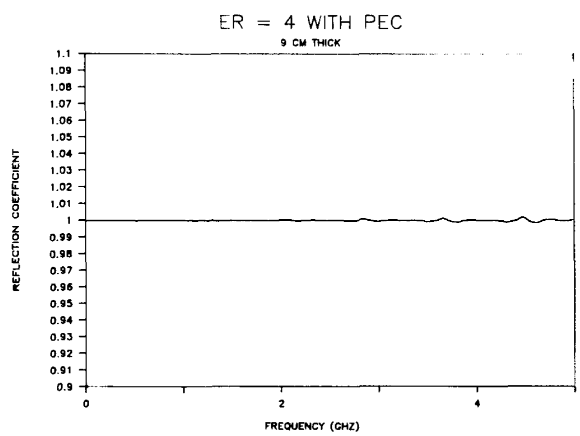


Fig. 7. Reflection coefficient versus frequency (based on Fourier transforms of FDTD results) for a dielectric slab of relative permittivity 4.0, 9 cm thick, backed by a perfect conductor.

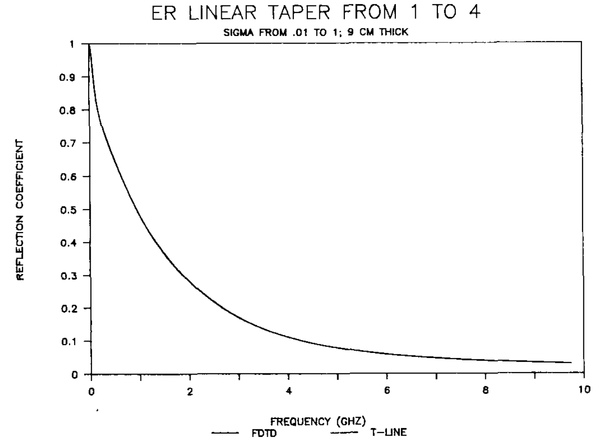


Fig. 8. Reflection coefficient versus frequency for a dielectric slab with relative permittivity linearly tapered from 1.0 to 4.0 and conductivity linearly tapered from 0.01 to 1.0 S/m calculated using Fourier transforms of FDTD results and compared to frequency-domain transmission line calculation.

Finally, Fig. 8 has the relative permittivity increase linearly from 1 to 4 and the conductivity increase linearly from 0.01 S/m at the front of the slab to 1.0 S/m at the back of the slab. Also shown are the direct frequency domain calculations for comparison purposes, and the agreement (as expected) is excellent.

IV. PC Demonstration Program

A. Computer System Requirements

The code used to implement the FDTD demonstration is written in the C programming language. The graphic subroutines used to display and animate the electromagnetic wave are the standard library routines supported by the compiler used to generate the executable code (Microsoft Quick-C). The program will run on any IBM PC compatible computer with color graphics (CGA, EGA, or VGA) in addition to some monochrome graphic systems. The program checks the graphics hardware of the system on which it is operating, and gives an error message if there is an incompatibility.

A PC with a coprocessor is also recommended when using this model since program execution is quite slow without one, due to the large number of floating-point operations performed in updating the FDTD equations.

B. Model Operation

When the program is executed, the user is given the choice of either a brief set of instructions or entry into the FDTD model. Upon initial entry into the model, the user will observe a Gaussian-shaped electric field pulse propagating in free space toward a dielectric backed by a perfect conductor. The program will continue executing until one of the keyboard keys is pressed, whereupon execution

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will pause, and a list of menu options will be presented. The user can select one of these options by entering the appropriate number. Menu choices and the associated functions performed are listed below.

CONTINUE: The model continues execution from the point at which it was paused. None of the defining parameters is changed.

Reset: This initializes the Gaussian pulse to its starting position. The parameters defining the configuration remain at the last values entered by the user or at their default values if the user has not changed them.

CHANGE PARAMETERS: This option allows the user to define the modeled configuration. In particular, the user can define the 0.1 percent amplitude width of the Gaussian pulse, the electrical properties of the dielectric slab (permittivity, permeability, and conductivity), the units of length (inches or centimeters), the physical width of the dielectric slab, and the backing for that slab (perfect conductor or free space). For each of these parameters, the range of allowable values is listed, and the model will not permit values outside of that range to be entered.

SAVE XDATA: When this option is selected, the user is asked for a file name in wich the spatial data are to be stored. The data placed in that file are in ASCII, and represent the waveform displayed on the console at the time that the SAVE XDATA command is issued. In all, there are 256 lines of data in the file, each representing position (cm), and the corresponding electric field intensity.

SAVE TDATA: When this option is selected, the user is asked for a file name in which the temporal data are to be stored and the number of time steps to calculate. For subsequent DFT processing, the number of time steps should be a power of two. The file will contain one electric field intensity value on each line for each time step.

LIBRARY: This option enables the user to define, store, and retrieve model setup parameters, which include the electrical properties of the slab, the slab thickness, and the slab backing. These configurations are stored on the default disk with a user-specified name appended with a .cfg extension.

HELP: Provides a brief description of menu functions and operation.

EXIT: Exits program and returns to DOS.

C. DFT Capability

In order to demonstrate time to frequency transformation of FDTD results, an interactive DFT program is part of the demonstration model. The DFT program operates on electric field versus time data files generated by the SAVE TDATA option (see above) and produces complex Fourier transforms (amplitude versus frequency) of the time domain data. These can be graphically displayed on the computer screen.

V. Classroom Applications

The FDTD model described here has been used in several classroom situations, ranging from a simple demonstration of reflection/transmission at dissimilar boundaries to an analysis of model results both in time and frequency domains. The classes in which the model was used and the corresponding concepts discussed are given below.

Junior-Level Electromagnetics: The classroom demonstration was given subsequent to a typical development of the transmission-line equations. Emphasis was placed on the difference equation approach to solving Maxwell's equations in one dimension in order to prepare the students for the demonstration. It is worth noting that students did appear to gain greater insight into the time–space relationships defined by Maxwell's equations using the difference equations form, rather than from the frequency-domain form of those differential equations. The classroom demonstration itself was performed in one 50 min class and was presented via a projection monitor. Prior to running the model for a particular configuration, blackboard calculations were made regarding reflection, transmission, and attenuation coefficients. The expected results were then discussed, and estimates of field behavior at various times were sketched, based upon the calculated coefficients. The model was then run for the conditions discussed, as well as for a range of input parameters.

The model proved to be especially useful in explaining the concepts of group and phase velocities (dispersion). As described above, the program models a Gaussian pulse interacting with dissimilar media. Because of the inherently broad-spectrum nature of a Gaussian pulse, the effects resulting from the difference in group and phase velocities for lossy media are clearly evident, as seen in Fig. 2, which shows the dispersion of the incident Gaussian pulse after being reflected from a lossy dielectric. Explaining this phenomenon with the aid of the model appeared to provide insights that have not been realized by the authors using conventional blackboard derivations in the frequency domain.

In order to demonstrate a deficiency of the Yee FDTD approach, the "nonreflective" boundary $\epsilon_r = \mu_r$; $\sigma = 0$ was shown in illustrate the difference that can occur between a discrete and continuous solution (the FDTD solution does show a small reflection at the boundary).

Senior-Level Electromagnetics: The model was incorporated into a senior-level course where students were asked to duplicate FDTD results by first deriving a frequency-domain solution, and then transforming that solution into the time domain via numerical integration. Students were assigned the task of computing the time-domain electric field that would be reflected from a pure dielectric slab of thickness d, backed by a perfect conductor, assuming a Gaussian-shaped incident electric field pulse. Using the transmission line approach to solving this problem, the frequency-domain solution is given by the Fourier transform of a Gaussian pulse multiplied by the reflection coefficient for a shorted transmission line of length equal to the slab width and characteristic impedance equal to the intrinsic impedance of the slab. The

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time-domain solution is then obtained by numerically calculating the inverse Fourier transform of the frequency-domain result. The transformed frequency-domain and time-domain waveforms were nearly identical.

Student feedback on this assignment was quite positive. It demonstrated clearly the contrast between time- and frequency-domain analysis, in addition to providing further insights in to the relationship between the time and frequency domains.

Students can also be given assignments involving transforming FDTD results into the frequency domain for comparison to frequency-domain calculations. The reflection coefficient results of Section III of this paper can serve as examples of this type of assignment.

Graduate-Level Electromagnetics: The FDTD demonstration module was found to be very useful in teaching a graduate course in computational electromagnetics which included FDTD itself as subject material. The FDTD module was first used to illustrate the method. Then the various limitations were demonstrated. For example, the high-frequency limit ($\Delta x <<$ minimum wavelength) was demonstrated by reducing the pulse width, as demonstrated in Fig. 3 of this paper. The graduate students were then given access to the FDTD module, and were encouraged to use it to further familiarize themselves with the FDTD method.

VI. Summary and Conclusion

A one-dimensional formulation of the finite difference time-domain (FDTD) method based on the Yee algorithm was presented, along with several sets of plots illustrating time-domain plane wave pulse reflection and transmission. These included dispersion by lossy media. Transformation to the frequency domain for comparison purposes was illustrated by considering the reflection coefficient for a dielectric slab. These results clearly showed the superiority of the FDTD approach to illustrating real propagation phenomenon when compared to the more common bounce diagram, which cannot illustrate dispersion effects and is not so directly related to Maxwell's equations.

Following these examples, a personal computer FDTD demonstration program developed and used by the authors was described. Its usefulness in teaching electromagnetics fundamentals, Fourier transform applications, and the FDTD method itself was described based on the experiences of the authors.

Acknowledgment

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Availability

The Personal Computer FDTD demonstration program described in this paper is available from WaveWave, P.O. Box 608, Durham, NH 03824.

References

[1] K. S. Yee, "Numerical solutions of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 302-307, May 1966.

[2] G. Mur, "Absorbing boundary conditions for finite-difference approximation of the time-domain electromagnetic-field equations," *IEEE Trans. Electromag. Compat.*, vol. EMC-23, pp. 1073-1077, Nov. 1981.

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